

July 29, 2011

# Measurements of B meson decay rates and CP violating asymmetries

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## Abstract

Hadrons containing  $b$ -quarks represent a great opportunity to investigate the flavor sector of the Standard Model (SM) and to look for New Physics effects (NP). In this report we review the most up-to-date results on  $b$ -hadron decay rates and CP violating asymmetries: among other results, we report Branching Ratio ( $\mathcal{B}$ ) and CP Violation (CPV) of  $B^0$ ,  $B_s^0$  and  $\Lambda_b^0$  decay modes into pairs of charmless charged hadrons (pions, kaons and protons), the first search for CPV in  $B_s^0 \rightarrow \phi\phi$  decays and the first observation of  $B_s^0 \rightarrow K^{0*}\bar{K}^{0*}$  decay. Two new results from the CDF collaboration are reported: the first evidence of  $B_s^0 \rightarrow \pi^+\pi^-$  decay and the world's best measurement of  $\mathcal{B}(B^0 \rightarrow K^+K^-)$ .

PRESENTED AT

The Ninth International Conference on  
Flavor Physics and CP Violation  
(FPCP 2011)  
Maale Hachamisha, Israel, May 23–27, 2011

# 1 Introduction

The interpretation of the CP violation mechanism is one of the most controversial aspects of the Standard Model. Many extensions of Standard Model predict that there are new sources of CP violation, beyond the single Kobayashi-Maskawa phase in the quark-mixing matrix (CKM). Considerations related to the observed baryon asymmetry of the Universe imply that such new sources should exist.

The non-leptonic decays of  $b$  hadrons into pairs of charmless charged hadrons are effective probes of the CKM matrix and sensitive to potential new physics effects. The large production cross section of  $b$  hadrons of all kinds at the TeVatron and LHC allows extending such measurements to  $B_s^0$  and  $\Lambda_b^0$  decays, which are important to supplement our understanding of  $B^0$  and  $B^+$  meson decays provided by the  $B$ -factories. The branching fraction of  $B_s^0 \rightarrow K^-\pi^+$  decay mode provides information on the CKM angle  $\gamma$  [1] and the measurement of direct CP asymmetry could be a powerful model-independent test of the source of CP asymmetry in the  $B$  system [2]. The  $B_s^0 \rightarrow \pi^+\pi^-$  and  $B^0 \rightarrow K^+K^-$  decay modes proceed through annihilation and exchange topologies, which are currently poorly known and a source of significant uncertainty in many theoretical calculations [3, 4]. A measurement of both decay modes would allow a determination of the strength of these amplitudes [5].

The measurement of the  $B_s^0 \rightarrow K^+K^-$  lifetime may be used to put constraints on contributions from NP to the  $B_s^0$  mixing phase and the width difference between the light and the heavy states in the  $B_s^0$  system  $\Delta\Gamma_s$ . In addition,  $B_s^0 \rightarrow K^+K^-$  decay being dominated by loop diagrams, new particles entering the loop processes can significantly influence  $B_s^0 \rightarrow K^+K^-$  decay.

Present CDF statistics of the  $B_s^0 \rightarrow \phi\phi$  data sample allows investigations of the Triple Product asymmetries, a class of CP-violation observables which can reveal the presence of NP [6].

$B_s^0 \rightarrow K^{0*}\bar{K}^{0*}$  is a decay into two light vector mesons that proceeds solely through loop penguin  $b \rightarrow s$  diagrams within the SM. The interest in  $B_s^0 \rightarrow K^{0*}\bar{K}^{0*}$  is related to the extraction of  $\beta_s$  and  $\gamma$  [7].

Throughout this paper, C-conjugate modes are implied and branching fractions indicate CP-averages unless otherwise stated. In addition, the first uncertainty associated with any number is statistical, while the second one is systematic.

## 2 CDF II

The Collider Detector at Fermilab (CDF II) experiment is a multipurpose magnetic spectrometer surrounded by calorimeters and muon detectors [8]. A silicon micro-strip detector (SVXII) and a cylindrical drift chamber (COT) situated in a 1.4 T solenoidal magnetic field reconstruct charged particles in the pseudo-rapidity range

$|\eta| < 1.0$ . The transverse momentum resolution is  $\sigma_{p_T}/p_T \simeq 0.15\% p_T/(\text{GeV}/c)$  and the observed mass-widths are about  $14 \text{ MeV}/c^2$  for  $J/\psi \rightarrow \mu^+\mu^-$  decays, and about  $9 \text{ MeV}/c^2$  for  $D^0 \rightarrow K^-\pi^+$  decays. The specific energy loss by ionization ( $dE/dx$ ) of charged particles in the COT is measured from the amount of charge collected by each wire. An average separation power of 1.4 Gaussian-equivalent standard deviation ( $\sigma$ ) is obtained in separating pions and kaons with momentum larger than  $2 \text{ GeV}/c$ . Consequently the separation between  $KK$  and  $\pi\pi$ , or  $K^+\pi^-$  and  $K^-\pi^+$  corresponds to about  $2.0 \sigma$ .

### 3 LHCb

The LHCb detector [9] is a forward spectrometer covering the pseudo-rapidity range  $1.8 < \eta < 4.9$ , designed to perform flavour physics measurement at the LHC and composed of several specialized sub-systems. The tracking system consists of a vertex detector, which allows an accurate reconstruction of the primary vertex, and a set of tracking stations in front of and behind a dipole magnet that provides a field of  $4 \text{ Tm}$ . Overall, the tracking system provides an impact parameter resolution of  $\sim 16 \mu\text{m} + 30 \mu\text{m}/p_T(\text{GeV}/c)$ , and a momentum resolution that ranges from  $\sigma/p \sim 0.5\%$  at  $3 \text{ GeV}/c$  and to  $\sim 0.8\%$  at  $100 \text{ GeV}/c$ . Two RICH (Ring-Imaging Cherenkov) detectors are used together and provide a typical kaon efficiency of  $\sim 95\%$  for a pion fake rate of a few percent, integrated over the momentum range from  $3\text{-}100 \text{ GeV}/c$ . Downstream of the second RICH are a Preshower/Scintillating Pad Detector, an electromagnetic calorimeter, a hadronic calorimeter and 5 muon chambers.

### 4 First evidence of $B_s^0 \rightarrow \pi^+\pi^-$ decay at CDF

The extraction of CKM parameters from measurements in  $b$ -hadron decays is often affected by large uncertainties, coming from non-perturbative QCD effects. One way to simplify the problem is to use flavor symmetries under which the unknown effects partially cancel. Therefore the simultaneous study of  $B^0 \rightarrow hh$  and  $B_s^0 \rightarrow hh$  decays (where  $h$  can be a pion or a kaon) is particularly interesting since these modes are related by subgroups of the  $\text{SU}(3)$  symmetry. Significant contributions from higher-order (“penguin”) transitions provide sensitivity to the possible presence of NP in internal loops, if the observed decay rates are inconsistent with expectations. Of the possible  $B \rightarrow hh'$  decay modes only the  $B_s^0 \rightarrow \pi^+\pi^-$  and  $B^0 \rightarrow K^+K^-$  observations are still missing. A measurement of the  $\mathcal{B}$  of the  $B_s^0 \rightarrow \pi^+\pi^-$  mode, along with the  $B^0 \rightarrow K^+K^-$  mode, would allow a determination of the strength of penguin-annihilation amplitudes, which is currently poorly known and source of significant uncertainty in many calculations.

CDF analyzed an integrated luminosity  $\int \mathcal{L} dt \simeq 6 \text{ fb}^{-1}$  sample of pairs of oppositely-charged particles with  $p_T > 2 \text{ GeV}/c$  and  $p_T(1) + p_T(2) > 5.5 \text{ GeV}/c$ , used to form  $B$  candidates. The trigger required also a transverse opening angle  $20^\circ < \Delta\phi < 135^\circ$  between the two tracks, to reject background from particle pairs within the same jet and from back-to-back jets. In addition, both charged particles were required to originate from a displaced vertex with a large impact parameter ( $100 \mu\text{m} < d_0(1, 2) < 1 \text{ mm}$ ), while the  $b$ -hadron candidate was required to be produced in the primary  $\bar{p}p$  interaction ( $d_0 < 140 \mu\text{m}$ ) and to have travelled a transverse distance  $L_T > 200 \mu\text{m}$ . A sample of about 3 million  $B \rightarrow hh'$  decay modes (where  $B = B^0, B_s^0$  or  $\Lambda_b^0$  and  $h = K$  or  $\pi$ ) was reconstructed after the off-line confirmation of trigger requirements. In the offline analysis, an unbiased optimization procedure determined a tightened selection on track-pairs fit to a common decay vertex. The offline selection is based on a more accurate determination of the same quantities used in the trigger, with the addition of two further observables: the isolation ( $I_B$ ) of the  $B$  candidate [10], and the quality of the three-dimensional fit ( $\chi^2$  with 1 d.o.f.) of the decay vertex of the  $B$  candidate. Requiring a large value of  $I_B$  reduces the background from light-quark jets, and a low  $\chi^2$  reduces the background from decays of different long-lived particles within the event. The final selection, inherited from Ref. [11], was originally devised for the  $B_s^0 \rightarrow K^- \pi^+$  search, but has proven to be optimal also for detection of the  $B_s^0 \rightarrow \pi^+ \pi^-$  and includes the following criteria:  $I_B > 0.525$ ,  $\chi^2 < 5$ ,  $d > 120 \mu\text{m}$ ,  $d_B < 60 \mu\text{m}$ , and  $L_T > 350 \mu\text{m}$ . No more than one  $B$  candidate per event is found after this selection, and a mass ( $m_{\pi\pi}$ ) is assigned to each, using a charged pion mass assignment for both decay products.

The resulting  $\pi\pi$ -mass distributions (see Figure 1, (a)) show a clean signal of  $B \rightarrow hh'$  decays. Backgrounds include mis-reconstructed multibody  $b$ -hadron decays (physics background, causing the enhancement at  $m_{\pi\pi} < 5.16 \text{ GeV}/c^2$ ) and random pairs of charged particles (combinatorial background). In spite of a good mass resolution ( $\approx 22 \text{ MeV}/c^2$ ), the various  $B \rightarrow hh'$  modes overlap into an unresolved mass peak near the nominal  $B^0$  mass, with a width of about  $\approx 35 \text{ MeV}/c^2$ .

The resolution in invariant mass and in particle identification, provided by specific ionization energy loss ( $dE/dx$ ) in the drift chamber, is not sufficient for separating the individual  $B \rightarrow hh'$  decay modes on an event-by-event basis, therefore a Maximum Likelihood fit, incorporating kinematics and PID information, was performed. The kinematic information is summarized by three loosely correlated observables: (a) the square of the invariant  $\pi\pi$  mass  $m_{\pi\pi}^2$ ; (b) the signed momentum imbalance  $\beta = (p_+ - p_-)/(p_+ + p_-)$ , where  $p_+$  ( $p_-$ ) is the momentum of the positive (negative) particle; (c) the scalar sum of particle momenta  $p_{\text{tot}} = p_+ + p_-$ . The likelihood exploits the kinematic differences among modes (see Figure 1, (b)) by using the correlation between the signed momenta of the tracks and the invariant masses  $m_{+-}^2$  of a candidate for any mass assignment of the decay products ( $m_+, m_-$ ), using the



physics background shape and kinematics,  $b$ -hadron masses and lifetimes.

The signal yields are calculated from the signal fractions returned by the likelihood fit. For the first time significant signal is seen for  $B_s^0 \rightarrow \pi^+\pi^-$ , with a significance of  $3.7\sigma$ , while the significance for the  $B^0 \rightarrow K^+K^-$  decay mode is  $2.0\sigma$ . The significances were estimated combining the statistical significance returned by the fit and a systematic uncertainty evaluated using the Likelihood Ratio distribution (distributed with good approximation as a  $\chi^2$  distribution) on pseudo-experiments.

| Mode                           | Quantity   | Relative $\mathcal{B}$      | Absolute $\mathcal{B}(10^{-6})$                  |
|--------------------------------|--|-----------------------------|--|
| $B^0 \rightarrow K^+K^-$       | $\frac{\mathcal{B}(B^0 \rightarrow K^+K^-)}{\mathcal{B}(B^0 \rightarrow K^+\pi^-)}$                              | $0.012 \pm 0.005 \pm 0.005$ | $0.23 \pm 0.10 \pm 0.10$ ([0.05, 0.46] @ 90% CL) |
| $B_s^0 \rightarrow \pi^+\pi^-$ | $\frac{f_s}{f_d} \times \frac{\mathcal{B}(B_s^0 \rightarrow \pi^+\pi^-)}{\mathcal{B}(B^0 \rightarrow K^+\pi^-)}$ | $0.008 \pm 0.002 \pm 0.001$ | $0.57 \pm 0.15 \pm 0.10$                         |

Table 1: Branching fractions results [12]. Absolute branching fractions are normalized to the the world-average values  $\mathcal{B}(B^0 \rightarrow K^+\pi^-) = (19.4 \pm 0.6) \times 10^{-6}$  and  $f_s/f_d = 0.282 \pm 0.038$  [13].

The relative branching fractions are listed in Table 1, where  $f_d$  and  $f_s$  indicate the production fractions respectively of  $B^0$  and  $B_s^0$  from fragmentation of a  $b$  quark in  $\bar{p}p$  collisions. Absolute results are also listed in Table 1; they are obtained by normalizing the data to the world-average of  $\mathcal{B}(B^0 \rightarrow K^+\pi^-)$  [13]. An 90% of confidence level interval is also quoted for the  $B^0 \rightarrow K^+K^-$  mode.

The present measurement of  $\mathcal{B}(B^0 \rightarrow K^+K^-)$  is the world's best measurement and supersedes the previous limit [14]. The central value is in agreement with other existing measurements [13], while it is higher than the predictions [15][16].

The branching fraction of the  $B_s^0 \rightarrow \pi^+\pi^-$  mode is consistent with the previous upper limit ( $< 1.2 \times 10^{-6}$  at 90% C.L.), based on a subsample of the current data [11], and is better than other existing measurements [17]; it is in agreement with the theoretical expectations within the pQCD approach [18], [19] while is higher than most other predictions [15] [20] [21] [22].

More details on the analysis can be found in [12].

## 5 Other $\mathcal{B}$ and CPV measurements of $B \rightarrow hh'$ decays

$B_{(s)}^0 \rightarrow h^+h'^-$  decays make possible a rich flavor-physics program at the B-factories and at the hadron machines. The branching fraction of  $B_s^0 \rightarrow K^-\pi^+$  decay mode provides information on the CKM angle  $\gamma$  [1] and the measurement of direct CP asymmetry could be a powerful model-independent test of the source of CP asymmetry in the  $B$  system [2]. As recently suggested from Lipkin [23], probably solving this puzzle, a discrepancy between the direct CP asymmetries in the  $B^0 \rightarrow K^+\pi^-$  and  $B^+ \rightarrow K^+\pi^0$  decays is expected within the SM, and it is experimentally observed [13].

Nevertheless, high accuracy measurements of  $\mathcal{A}_{\text{CP}}(B^0 \rightarrow K^+\pi^-)$  and  $\mathcal{A}_{\text{CP}}(B_s^0 \rightarrow K^-\pi^+)$  may provide useful information to our comprehension of this discrepancy. CP violating asymmetries in  $\Lambda_b^0 \rightarrow p\pi^-$  and  $\Lambda_b^0 \rightarrow pK^-$  decay modes may reach significant size  $\mathcal{O}(10\%)$  in the Standard Model [24]. Measurements of asymmetries and branching fractions of these modes may favor or disfavor some specific extensions or would rule out (or allow) some extensions of the SM [25].

We report a comparison of the most up-to-date measurements performed by Belle [17], [26], [27], BaBar [29], CDF [11], [30], and LHCb [31] of  $\mathcal{B}$  and CPV asymmetries of  $B \rightarrow hh'$  decay modes (see tab. 2, tab. 3, tab. 4). CDF measurements on  $B^0$  and  $B_s^0$  sector are in agreement and competitive with the results from B-factories. In particular,  $\mathcal{A}_{\text{CP}}(B_s^0 \rightarrow K^-\pi^+)$  the measurements for the  $\Lambda_b^0$  sector represent the first measurement of these observables.

| Mode                         | CDF                      |                           | BaBar                           |  | Belle |
|------------------------------|--------------------------|---------------------------|---------------------------------|--|-------|
|                              | 1fb <sup>-1</sup>        | 467 M ( $B\bar{B}$ pairs) | 535 M ( $B\bar{B}$ pairs)       |  |       |
| $B^0 \rightarrow K^+\pi^-$   |                          | $19.1 \pm 0.6 \pm 0.6$    | $19.9 \pm 0.4 \pm 0.8$          |  |       |
| $B^0 \rightarrow \pi^+\pi^-$ | $5.02 \pm 0.33 \pm 0.35$ | $5.5 \pm 0.4 \pm 0.3$     | $5.1 \pm 0.2 \pm 0.2$           |  |       |
| $B^0 \rightarrow K^+K^-$     | $0.39 \pm 0.16 \pm 0.12$ | $0.04 \pm 0.15 \pm 0.08$  | $0.09^{+0.18}_{-0.13} \pm 0.01$ |  |       |

Table 2:  $\mathcal{B}$  ( $10^{-6}$ ) of  $B^0$  decay modes

LHCb recently reported its first preliminary results for  $\mathcal{A}_{\text{CP}}(B^0 \rightarrow K^+\pi^-)$  and  $\mathcal{A}_{\text{CP}}(B_s^0 \rightarrow K^-\pi^+)$ , using 37 pb<sup>-1</sup> of data [31] (see tab. 5). LHC being a hadron collider, LHCb shares with CDF II some environment related characteristics, such as: high  $b$ -hadron production, specific trigger requirements for B-physics and, therefore, the analysis strategy is similar. In addition, LHCb benefits from the different detector structure and skills. In particular, the presence at LHCb of the RICH detectors makes possible a powerful particle identification. The efficiency in identifying the final states particles gives the possibility to measure CP-asymmetries with very competitive

| Mode                            | CDF<br>1fb <sup>-1</sup>                  | Belle<br>23.6 fb <sup>-1</sup>      |
|---------------------------------|---|-------------------------------------|
| $B_s^0 \rightarrow K^- \pi^+$   | $5.0 \pm 0.7 \pm 0.8$                     | (< 26 @ 90% CL)                     |
| $B_s^0 \rightarrow \pi^+ \pi^-$ | $0.49 \pm 0.28 \pm 0.36$ (< 1.2 @ 90% CL) | (< 12 @ 90% CL)                     |
| $B_s^0 \rightarrow K^+ K^-$     |   | $38 \pm_{-9}^{10} \pm 5 \pm 5(f_s)$ |

Table 3:  $\mathcal{B}$  (10<sup>-6</sup>) of  $B_s^0$  decay modes

| Mode                              | CDF<br>1fb <sup>-1</sup>     | BaBar<br>467 M ( $B\bar{B}$ pairs)       | Belle<br>535 M ( $B\bar{B}$ pairs) |
|-----------------------------------|------------------------------|--|------------------------------------|
| $B^0 \rightarrow K^+ \pi^-$       | $-0.086 \pm 0.023 \pm 0.009$ | $-0.107 \pm 0.016 \pm_{-0.004}^{+0.006}$ | $-0.094 \pm 0.018 \pm 0.008$       |
| $B_s^0 \rightarrow K^- \pi^+$     | $+0.39 \pm 0.15 \pm 0.08$    |  |                                    |
| $\Lambda_b^0 \rightarrow p K^-$   | $+0.37 \pm 0.17 \pm 0.03$    |  |                                    |
| $\Lambda_b^0 \rightarrow p \pi^-$ | $+0.03 \pm 0.17 \pm 0.05$    |  |                                    |

Table 4:  $\mathcal{A}_{\text{CP}}$  of  $B \rightarrow hh'$  decay modes

statistical uncertainties even if using only the small amount of data corresponding to about 37 pb<sup>-1</sup> of integrated luminosity.

| Mode                          | LHCb                         |
|-------------------------------|------------------------------|
| $B^0 \rightarrow K^+ \pi^-$   | $-0.074 \pm 0.033 \pm 0.008$ |
| $B_s^0 \rightarrow K^- \pi^+$ | $0.15 \pm 0.19 \pm 0.02$     |

Table 5: Preliminary LHCb results for  $\mathcal{A}_{\text{CP}}$  of  $B_s^0 \rightarrow K^- \pi^+$  and  $B^0 \rightarrow K^+ \pi^-$  decay modes.



## 6 Measurement of $B_s^0 \rightarrow K^+ K^-$ lifetime

Using a sample of about  $360 \text{ pb}^{-1}$  CDF measured the time-evolution of untagged  $B_s^0 \rightarrow K^+ K^-$  decays [32]. An unbiased optimization procedure, similar to the one used for  $B \rightarrow hh'$  analysis, aimed at improving the resolution on lifetime-measurements, yielded an offline selection based on transverse-momentum, impact-parameter, and vertex-quality requirements. The resulting signal was similar, with less statistics, to the one shown in the left plot of fig. 1, and contained about 2200  $B_s^0 \rightarrow K^+ K^-$  decays. The time evolution of individual signal modes was determined by adding the decay-length information to the fit of composition, similar to the one described in the previous sections for the CDF analysis with  $6 \text{ fb}^{-1}$ . The selection of the sample of B mesons decaying into two hadrons makes minimum requirements on the flight distance of the B meson, both during data-taking and in the final event selection. Consequently, the selection procedure tends to reject candidates which decay after a short proper time. This bias of the distribution was modeled with an efficiency curve, defined as the ratio between the pseudo-proper decay-length distribution of events passing the trigger and the unsculpted one, and it was extracted from simulations. The dominant sources of systematics come from effects of misalignments in the tracker, uncertainties on the model used from proper-decay time resolution and for the lifetime of background, the uncertainty of  $dE/dx$  model, the uncertainty on the input  $p_T(B)$  spectrum used in the simulation and the uncertainty on the extraction of the trigger-efficiency curve. The resulting lifetime is

$$\tau_L(B_s^0 \rightarrow K^+ K^-) = 1.53 \pm 0.18 \pm 0.02 \text{ ps.}$$

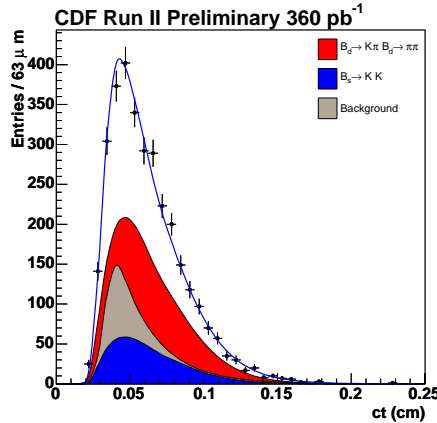


Figure 2: Likelihood function projection on the proper decay length projection. The different contributions of  $B^0$  and  $B_s^0$  signals and of the background are overlaid.

The lifetime distribution of the signal with fit projection overlaid is shown in fig. 2.

Two independent data-driven approaches are used at LHCb to compensate for the bias of the distribution [33]. In the first one the absolute lifetime is measured by correcting for the biases by determining the event-by-event acceptance function. The lifetime is determined by an unbinned maximum likelihood fit using an analytical p.d.f. for the signal lifetime and a non-parametric estimated p.d.f. for the combinatorial background. The measurement is factorised in two independent fits. A first fit is performed to the observed mass spectrum and used to determine the signal and background probabilities of each event. These probabilities are used in the subsequent fit for the lifetime. The p.d.f. describing the lifetime of the signal is calculated analytically taking into account per-event acceptance and the proper time resolution. The p.d.f. of the combinatorial background is estimated from the data using a non-parametric method, described as a sum of one Gaussian kernel per event. The mean of the Gaussian Kernel is the measured proper time, the area of the Gaussian is weighted by the background probability of the event. The per-event acceptance is calculated by re-running the event selection, determining whether an event would have been selected as a function of its proper time. For example, for an event with given kinematics, i.e. fixed track slopes and momenta, there is a direct relation between the proper time and the impact parameters of the tracks. Hence, cuts on impact parameters directly translate into a discrete decision about acceptance or rejection of an event as a function of its proper time.

The second approach cancels the selection bias by taking a ratio of the  $B_s^0 \rightarrow K^+K^-$  and  $B^0 \rightarrow K^+\pi^-$  proper decay time distributions, exploiting the fact that  $B_s^0 \rightarrow K^+K^-$  and  $B^0 \rightarrow K^+\pi^-$  have similar kinematics. The reliability of the procedure has been tested using a toy simulation and realistic events including the simulation of the full detector response. The  $B_s^0 \rightarrow K^+K^-$  lifetime is fitted for directly by means of a simultaneous fit of both final states and  $\xi$  bins, where  $\xi = \frac{t}{m}$  is the reduced proper time.  $m$  is the invariant mass with the assignment of two pions in the final state, and therefore  $\xi$  is introduced to avoid any potential bias due to a miscalculation of the candidate's proper time in the case where the final state is different from  $\pi\pi$ .

The dominant sources of systematics for the two measurements are contamination from other  $B \rightarrow hh'$  decay modes, the uncertainty on the distributions of combinatorial background, the correction of the bias, the effects of misalignments in the tracker. A systematics taking into account that in events with multiple primary vertices the B meson candidate may be assigned to the wrong vertex and hence its lifetime is wrongly calculated is also assessed. The two measurements of the  $B_s^0 \rightarrow K^+K^-$  lifetime agree well, and using the world average measurement of the  $B^0 \rightarrow K^+\pi^-$  lifetime as input you can extract the  $B_s^0 \rightarrow K^+K^-$  lifetime:

$$\tau_{B_s^0} = 1.440 \pm 0.096 \pm 0.010 \text{ps.}$$

## 7 First search for CP violation in $B_s^0 \rightarrow \phi\phi$ decay modes

The  $B_s^0 \rightarrow \phi\phi$  decay belongs to the class of transitions of pseudoscalar mesons into two vector particles ( $P \rightarrow VV$ ), whose rich dynamics involves three different amplitudes corresponding to the polarization states. In the SM the dominant quark level process is described by the  $b \rightarrow s$  penguin diagram. Hence this decay mode could provide sensitivity to the possible presence of NP in internal loops. Indeed, the SM expectation for polarization amplitudes have shown discrepancies with measurements of similar penguin decays [34]. Moreover, having a self-conjugate final state, the  $B_s^0 \rightarrow \phi\phi$  allows for measuring the  $B_s^0$  decay width difference  $\Delta\Gamma_s$ , and it is sensitive to the CP violation in the interference between decay with and without mixing, supplementing analogous studies in the tree dominated  $B_s^0 \rightarrow J/\psi\phi$ . Actually, the CP violating weak phase  $\phi_s^{\phi\phi}$  is predicted to be extremely small in the SM and measurement of nonzero CP-violating observables would indicate unambiguously NP.

The first evidence for the  $B_s^0 \rightarrow \phi\phi$  decay has been reported by CDF in 2005 [35]. Using  $2.9 \text{ fb}^{-1}$  of data, the branching ratio measurement was recently updated [36],  $BR(B_s^0 \rightarrow \phi\phi) = (2.40 \pm 0.21 \pm 0.86) \times 10^{-5}$ , in agreement with the first determination. Signal candidates are reconstructed by detecting  $\phi \rightarrow K^+K^-$  decays and are formed by fitting four tracks to a common vertex. Combinatorial background is reduced by exploiting several variables sensitive to the long lifetime and relatively hard  $p_T$  spectrum of  $B$  mesons, while the physics background, given by  $B^0 \rightarrow \phi K^*(892)^0$  decay, is estimated by simulation not to exceed a 3% fraction of the signal. Signals of  $295 \pm 20$  events are obtained by fitting the mass distribution. This data sample has allowed the world's first polarization measurement [36] by analyzing the angular distributions of decay products, expressed as a function of helicity angles,  $\vec{\omega} = (\cos\vartheta_1, \cos\vartheta_2, \Phi)$ . The total decay width is composed of three polarization amplitudes: two CP-even ( $A_0$  and  $A_{\parallel}$ ) and one CP-odd ( $A_{\perp}$ ). The measured amplitudes result in a smaller longitudinal fraction with respect to the naïve expectation,  $f_L = 0.348 \pm 0.041 \pm 0.021$ , as found in other similar  $b \rightarrow s$  penguin decays [34].

Present statistics of the  $B_s^0 \rightarrow \phi\phi$  data sample are not sufficient for a suitable time-dependent analysis of mixing-induced CP-violation as the case of the  $B_s^0 \rightarrow J/\psi\phi$  decay. However, an investigation of genuine CP-violating observables which could reveal the presence of NP, such as triple products (TP) correlations, is accessible [37]. The TP is expressed as  $\vec{p} \cdot (\vec{\epsilon}_1 \times \vec{\epsilon}_2)$ , where  $\vec{p}$  is the momentum of one of the  $\phi$  meson in the  $B_s^0$  rest frame, and  $\vec{\epsilon}_i$  are the polarization vectors of the vector mesons. There are two triple products in the  $B_s^0 \rightarrow \phi\phi$  decay corresponding to interferences between CP-odd and CP-even amplitudes, one for transverse-longitudinal mixture,  $\Im(A_0 A_{\perp}^*)$ , and the other for the transverse-transverse term,  $\Im(A_{\parallel} A_{\perp}^*)$ . These products are functions of the helicity angles: the former is defined by  $v = \sin\Phi$  for  $\cos\vartheta_1 \cos\vartheta_2 \geq 0$  and

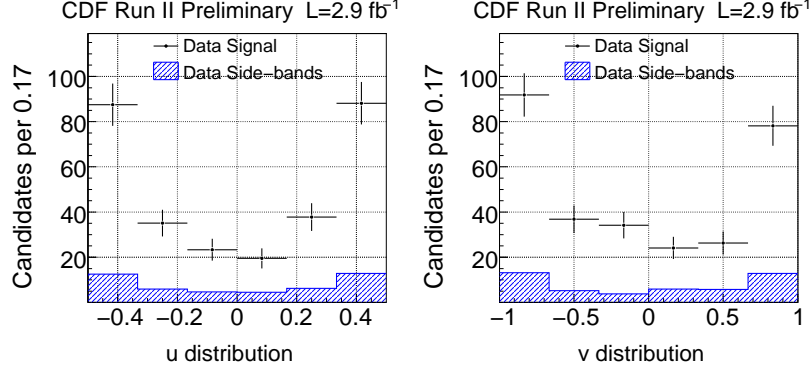


Figure 3: Distribution of  $u$  (left) and  $v$  (right) for  $B_s^0 \rightarrow \phi\phi$  candidates. Black crosses are background-subtracted data; the blue histogram represents the background.

$v = -\sin \Phi$  for  $\cos \vartheta_1 \cos \vartheta_2 < 0$ ; the latter is defined by  $u = \sin 2\Phi$ . The  $u$  and  $v$  distribution for  $B_s^0 \rightarrow \phi\phi$  candidates are shown in fig 3. Without distinction of the flavor of the  $B_s^0$  meson at the production time (*untagged* sample), the following equation defines a CP-violating asymmetry:

$$\mathcal{A}_u = \frac{\Gamma(u > 0) + \bar{\Gamma}(u > 0) - \Gamma(u < 0) - \bar{\Gamma}(u < 0)}{\Gamma(u > 0) + \bar{\Gamma}(u > 0) + \Gamma(u < 0) + \bar{\Gamma}(u < 0)}, \quad (2)$$

where  $\Gamma$  is the decay rate for the given process and  $\bar{\Gamma}$  is its CP-conjugate. An equivalent definition holds for  $v$ . Being proportional to  $\sin \phi_s \cos \delta_i$ , where  $\delta_i$  are relative strong phases between the polarization amplitudes, in  $B_s^0 \rightarrow \phi\phi$  these asymmetries are nonzero only in presence of NP [37].

The CDF collaboration has made the first measurement of  $\mathcal{A}_u$  and  $\mathcal{A}_v$  asymmetries in  $B_s^0 \rightarrow \phi\phi$  using the data sample described above [38]. The asymmetries are obtained through an unbinned maximum likelihood fit. The sample is split into two subsets according to the sign of  $u$  (or  $v$ ) of  $B_s^0 \rightarrow \phi\phi$  candidates. The invariant mass distribution of each subset is fitted simultaneously in order to extract the signal asymmetry. The small fraction of physics background, such as  $B^0 \rightarrow \phi K^*(892)^0$  as well as non-resonant decay  $B_s^0 \rightarrow \phi K^+ K^-$  and “S-wave” contamination  $B_s^0 \rightarrow J/\psi f_0(980)$ , is neglected in the fit and its effect is accounted for in the assigned systematic uncertainties. Using a large sample of Monte Carlo (MC) data the detector acceptance and the reconstruction requirements are checked against biases with a 0.2% accuracy. The background asymmetries are consistent with zero, and the final results for signal asymmetries are:  $\mathcal{A}_u = (-0.7 \pm 6.4 \text{ (stat.)} \pm 1.8 \text{ (syst.)})\%$  and  $\mathcal{A}_v = (-12.0 \pm 6.4 \text{ (stat.)} \pm 1.6 \text{ (syst.)})\%$ . This measurement establishes a method to search for NP through CP-violating observables in  $P \rightarrow VV$  decays without the need of tagging and time-dependent analysis, which requires high statistics samples.

## 8 First observation of the decay $B_s^0 \rightarrow K^{*0} \bar{K}^{*0}$

$B_s^0 \rightarrow K^{*0} \bar{K}^{*0}$  is a decay into two light vector mesons that proceeds solely through loop penguin  $b \rightarrow s$  diagrams within the SM. The interest in  $B_s^0 \rightarrow K^{*0} \bar{K}^{*0}$  for precision CP violation studies in relation to the extraction of  $\beta_s$  and  $\gamma$  has been analyzed in [39], [40], [41]. Before the measurement we are going to present, the best measurement was an upper limit for the  $\mathcal{B}$  of  $1.68 \times 10^{-3}$ , given by the SLD experiment [42]. LHCb analyzed a data sample corresponding to about  $35 \text{ pb}^{-1}$  of integrated luminosity. The cuts selection is optimized to keep maximal efficiency for the simulated decays and minimum background from a sample where no signal is expected. The selection relies on the excellent vertexing capability of LHCb. The mass spectrum of the selected  $K^+ \pi^- K^- \pi^+$  is shown in fig. 4 where a clear peak is observed around the  $B_s^0$  mass.

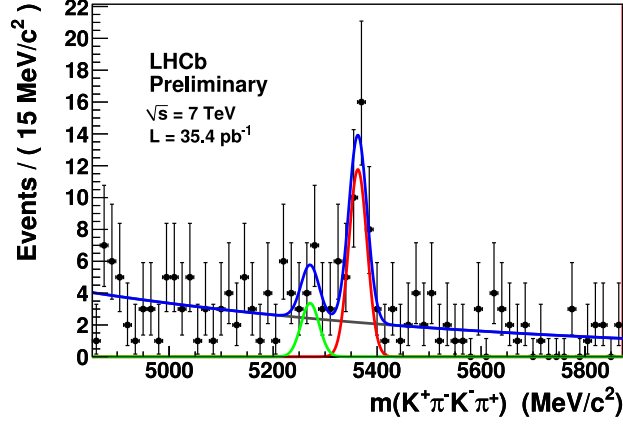


Figure 4: Fit to the  $K^+ \pi^- K^- \pi^+$  mass distribution for selected candidates. A gaussian function (red and green curves) is used for the  $B_s^0$  and  $B^0$  signals and an exponential function (blue curve) is used to describe the combinatorial background.

The significance of the  $B_s^0$  signal was evaluated using the two values of the log of the maximum likelihood obtained including a Gaussian  $B_s^0$  signal and fixing the  $B_s^0$  signal to zero (null hypothesis). The difference between the logs corresponds to  $7.4 \sigma$  significance. Both models include an exponential parameterization for the background, and a Gaussian signal for the  $B^0$  meson. When doing this test, the mass and width of the  $B_s^0$  meson were fixed to those obtained from an independent fit to LHCb data from the  $B_s^0 \rightarrow J/\psi \phi$  channel. Likewise, the  $B^0$  mass and width were input values from  $B^0 \rightarrow J/\psi \bar{K}^{*0}$ . An unbinned maximum likelihood fit was then performed, where the mass and width for the  $B_s^0$  gaussian signal were allowed to float, keeping the same exponential model to describe a combinatorial background.

An additional gaussian signal was included in the model to account for a possible contribution of a  $B^0$  meson decay to the same nal state. The fit confirm a signal of about  $34 \pm 7$  events for the decay  $B_s^0 \rightarrow K^{0*} \bar{K}^{0*}$ .

This result can be used to provide a determination of the  $\mathcal{B}$  of  $B_s^0 \rightarrow K^{0*} \bar{K}^{0*}$  using the normalization channel  $B^0 \rightarrow J/\psi \bar{K}^{*0}$  [13], and the selection and trigger efficiencies. The other ingredients are the b-quark hadronization factors  $f_s$  and  $f_d$  [43] to take into account the different yield of  $B^0$  and  $B_s^0$  mesons, and an acceptance correction. The result is

$$\mathcal{B}(B_s^0 \rightarrow K^{0*} \bar{K}^{0*}) = (1.95 \pm 0.47 \pm 0.51 \pm 0.29(f_d/f_s)) \times 10^{-5}$$

where the systematic error is composed by 22% uncertainty on the acceptance correction, 13% from trigger efficiencies, 6% from background subtraction and a separate error associated to the ratio  $f_d/f_s$ . More details can be found at [44].

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